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THE FIRST MODERN PNEUMATIC MACHINES, AND THEIR EFFECTS.

"In the history of human discovery," says Dr. Lardner, "there are few more impressive lessons of humility than that which is to be collected from the records of the progress by which the pressure of the atmosphere which surrounds us, and the manner in which it is instrumental in producing some most ordinary phenomena, became known. Looking back from the point to which we have now attained, and observing the numerous and obvious indications of this effect which present themselves at all times, and on all occasions, nature seems almost to have courted the philosopher to the discovery.

"The ancient philosophers observed that, in the instances which commonly fell under their notice space was always filled with a material substance. The moment a solid or a liquid was by any means removed, immediately the surrounding air rushed in and filled the place which it deserted: hence they adopted the physical dogma that *nature abhors a vacuum.*

"Probably one of the first ways in which the atmospheric pressure presented itself was by the effect of suction by the mouth. One end of a tube being immersed in a liquid, and the other being placed between the lips, the air was drawn from the tube by the ordinary process of inhaling. The water was immediately observed to fill the tube as the air retreated. This phenomenon was accounted for by declaring that 'nature abhorred a vacuum,' and that she therefore compelled the water to fill the space deserted by the air.

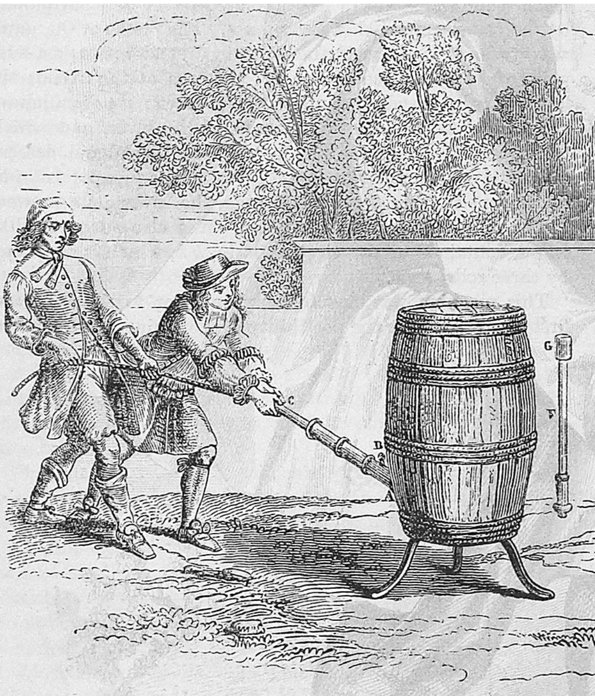

Fig. 1.—Otho Guericke attempting to produce a vacuum in a cask.

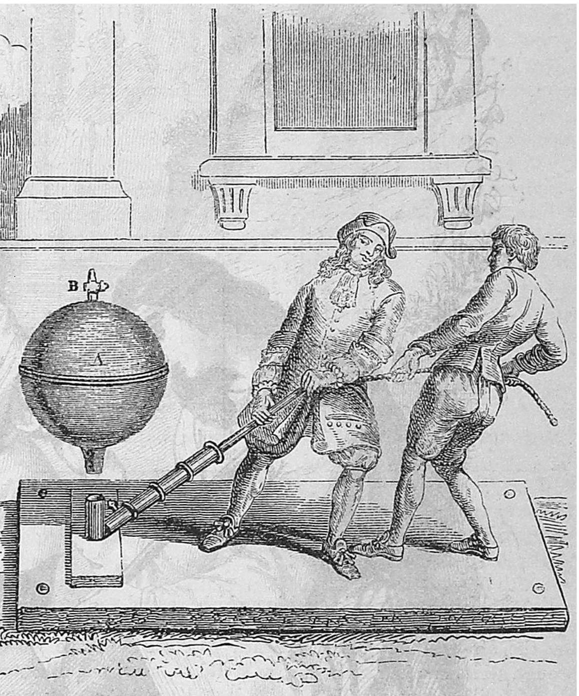

Fig. 2.—Second sort of receiver employed by Otho Guericke, to produce a vacuum.

"The effects of suction by the mouth led by a natural analogy to suction by artificial means. If a cylinder be open at both ends, and a piston playing in it air-tight be moved to the lower end, upon immersing the lower end in water, and then drawing up the piston, an unoccupied space would remain between the piston and the water. But 'nature abhors such a space,' said the ancients, 'and therefore the water will not allow such a space to remain unoccupied; we find accordingly that as the piston rises, the water follows it.' By such poetical reasoning, pumps of various kinds were constructed."

The antipathy nature had for an empty space served the purposes of philosophy for some two thousand years, when Torricelli demonstrated, in 1643, by his magnificent suspension of a column of quicksilver in a tube closed at its upper end, while its lower open extremity was plunged in a vessel filled with the same liquid, the possibility of obtaining a complete vacuum. Torricelli had argued, to again use the words of Dr. Lardner, "that whatever be the cause which sustained a column of water in a common pump, the measure and energy of that power must be the weight of the column of water; and, consequently, if another liquid be used, heavier or lighter, bulk for bulk, than water, then the same force must sustain a lesser or greater column of such liquid. By using a much heavier liquid, the column sustained would necessarily be much shorter, and the experiment in every way more manageable."

He consequently selected mercury, the heaviest known liquid, for his experiment, and the result was what he had anticipated, though the space in which the barometrical vacuum existed was too limited and too difficult of access to allow of any satisfactory suite of experiments being made.

The discovery of Torricelli had made a deep impression on Otho Guericke, a German philosopher. Born, in 1602, at Madgeburg, of which place he was burgomaster, and constantly employed in important political business, this distinguished man devoted all the time spared him by his official duties to scientific researches. He has himself transmitted to us, in a valuable work, an account of the numerous attempts he had made before discovering a somewhat practical means of producing a vacuum.

He first of all tried to draw the water out of a cock by the aid of a sort of syringe applied to the lower part of it.

Fig. 1 illustrates this attempt, with the details of the mechanism employed. A B C represents a metal pump into which the piston C or F G was carefully fitted, and which had two cocks: an interior one, at the orifice of the pump, A, to let in the water; and an external one, B, to procure a passage for the water thrown out. The orifice of the pump was attached, by four screws, to a circular iron plate. This apparatus broke, however, before the water could be drawn off.

Guericke lost none of his courage through this unsuccessful experiment. He employed a stronger apparatus; and, at last, three vigorous working men succeeded, by pulling at the piston of the syringe, in drawing off the water through the valve, B.

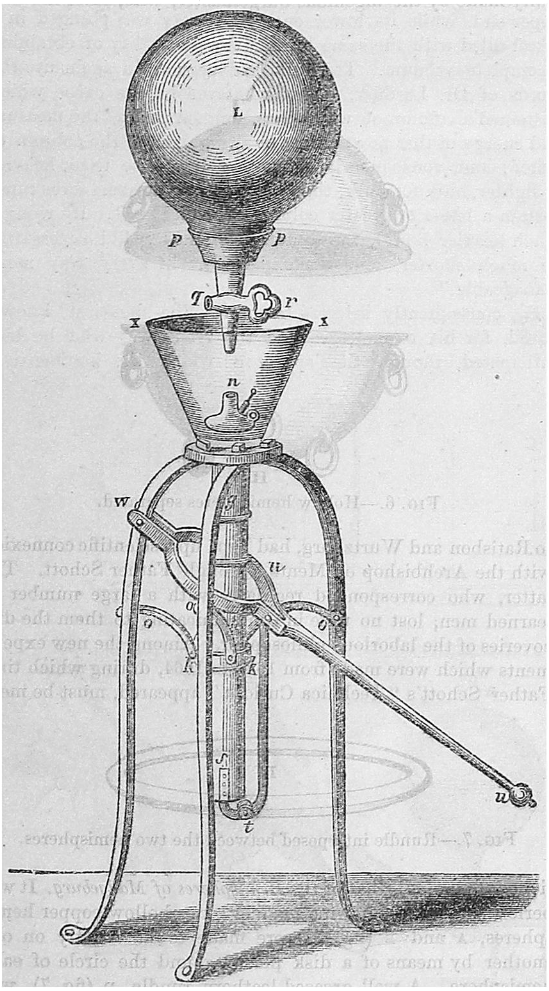

Fig. 3.—First pneumatic machine which worked regularly.

But the air was immediately heard to rush into the cask through all its cracks, producing, as it did so, a noise similar to that of boiling water. This noise lasted until the cask was completely filled with air. After a few other trials, it was perceived that wood was too permeable to both air and water, and another kind of receiver was, therefore, employed.

The wooden cask was now replaced by a copper globe, *a*, composed of two hemispheres fitting into each other (fig. 2). In the upper part, there was a cock, B, and the orifice of the pump was carefully fitted to the lower part. It was in this vessel, filled first with water, that a vacuum was attempted to be produced, in the same manner as had been employed with the wooden cask.

The piston met, at first, with no obstacle in its motion; but, little by little, it moved much harder, till, at last, two men of middling strength could scarcely draw it back. While they were thus employed in moving the piston backward and forward, and when nearly all the air was drawn off, the metallic globe, to the great terror of all present, suddenly collapsed with an explosion, and presented the appearance of having violently struck against the ground, after falling from a great height. Guericke rightly attributed this phenomenon to some imperfections in the manufacture of the vessel, and which had caused it to yield to the pressure of the air. He, therefore, had a new spherical receiver made, taking care that, this time, there was not the least irregularity in its form or make, and a vacuum was now produced without any accident whatever. It was then believed that the vacuum was complete when the pump sent no more air out of the receiver. But however that may be, the vacuum now produced gave rise to several remarkable phenomena. On opening the cask, B, the air rushed into the receiver with such impetuosity that those present felt themselves drawn along by the current; and when they placed their mouths near the opening, their breath was taken away: no one could put his hand on the turned-on cock, without feeling it drawn inwards and violently detained.

But, however perfect the vacuum might be in the interior of the receiver, it did not remain so long. The air again penetrated through the joinings of the cock and of the pump, and in two days' time, had entirely refilled the vessel. It was, therefore, sought to remedy this defect, and an apparatus was invented, which, after undergoing several successive improvements, assumed, at last, the form represented in fig. 3.

In this figure, the air-pump, *g h s*, is placed vertically on a tripod, whose three legs are fixed solidly in the ground. At the upper end of the pump is a tubulated vessel, *n*, to which the neck of the recipient, L, which is to be emptied, is fixed. To make the juncture more perfect, leathern rundles were used, while the joints in the tubulated vessel were surrounded by the water contained in a vase, X X. The piston of the pump was worked by a lever in the following manner:—W is a fixed point of rotation placed on one of the legs of the tripod; the lever, W *u*, is moved alternately up and down; *u t s* is a jointed rod which follows the movements of the lever, and which, consequently, causes the piston, *s k k*, to ascend and descend alternately in the interior of the barrel of the pump. In order to prevent the air from re-entering, the lower joint between the barrel of the pump and the piston is also surrounded by water, contained in the circular basin, *k k*, which is supported by three rods, *o o o*.

This machine was incontestably superior to the apparatus first used. Besides the possibility of obtaining a more perfect vacuum with less trouble, it also afforded the means of easily separating the receiver from the pump employed to produce the vacuum. In order to introduce various objects, such as birds, fish, rats, clocks, bells, lights, &c., when required for experiments, into the receiver, L, a large neck, *p p*, was fixed to it, and to this neck was fitted the cock, *q r*. It was in a

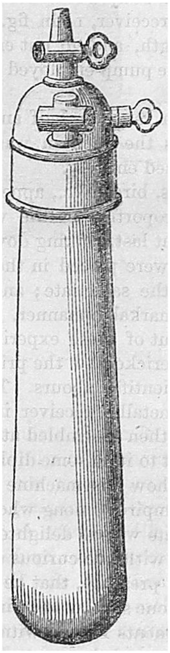

Fig. 4.—Receiver used for the first experiment made with the water-hammer.

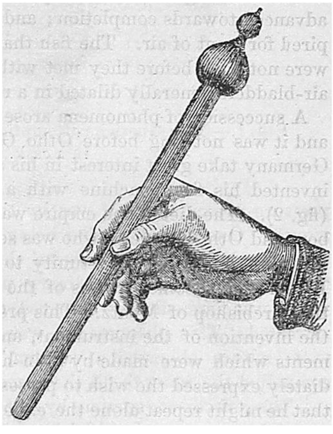

Fig. 5.—The water-hammer.

glass receiver, thus arranged, that a vacuum was produced for the first time, without its being previously filled with water.

Having succeeded thus far, Otho Guericke was enabled to make a series of very curious experiments, most of which are made, or ought to be made, at present in all schools of natural philosophy.

A vacuum being thus produced in the receiver, L, when the neck of this vessel is plunged in the water and the cock is turned on, the water is seen to rush with impetuosity and in a high state of commotion into the interior of the vessel, which, little by little, it fills entirely, with the exception perhaps of a small space of the size of a nut.

An oblong vase (fig. 4) having been, first of all, entirely filled with water, and then half-emptied by means of the air-pump, Otho Guericke was much surprised to see, on turning the vase sharply round, that the water struck against the ends of it with a noise similar to that which would have been produced by a blow from a hammer; and if the glass had not been very thick, the vase would have most certainly been broken. This experiment is at present made with an instrument called a *water-hammer*, which is made, without the assistance of the air-pump, in the following manner:

Take a strong glass tube, closed and rounded at one of its extremities; then half-fill it with water, which must be boiled in it. When the water has been boiling for some time, and the temperature has attained a high degree of heat, the upper extremity of the tube must be sealed by the means of an enameller's lamp.

By thus heating the water, all the air contained in it is expelled, while the steam drives out the air that fills the empty part of the tube. So, we have, at last, a tube hermetically closed at both ends, entirely cleared of air, and half-filled with water. By now simply turning this tube up and down, the water will strike against its ends with a noise and shock similar to those produced by a blow from a hammer; and by taking away the air-cushion, which generally divides any liquid when falling, the mass of water falls all together, and strikes against the glass as a solid body would do.

A light being placed in the glass receiver, L, in fig. 3, the flame will turn blue, increase in length, and go out entirely, after a few strokes of the piston of the pump employed to produce a vacuum.

The sound of a clock-bell, which rang for half an hour, diminished gradually in loudness as the vacuum was being produced, and, in a few instants, ceased entirely.

Various small animals, such as rats, birds, &c., appeared to breathe with greater difficulty in proportion as the vacuum advanced towards completion; and, at last, sinking down, expired for want of air. The fish that were placed in the water were not long before they met with the same fate; and their air-bladders generally dilated in a remarkable manner.

A succession of phenomena arose out of these experiments; and it was not long before Otho Guericke saw the princes of Germany take great interest in his scientific labours. He had invented his first machine with a metallic receiver in 1654 (fig. 2). The diet of the empire was then assembled at Ratisbon, and Otho Guericke, who was sent to it on some diplomatic business, found an opportunity to show his machine to the Emperor and some princes of the empire, among whom was the Archbishop of Mentz. This prelate was so delighted with the invention of the instrument, and with the curious experiments which were made by it in his presence, that he immediately expressed the wish to possess one similar to it, in order that he might repeat alone the experiments he had witnessed; but the short stay he made at Ratisbon, and the want of workmen, prevented his wish from being immediately gratified. He, however, invited Otho Guericke to come to see him in his palace, at Wurtzburg, and begged him to bring his machine with him. It was there that Father Schott, who taught mathematics, and several other learned men, first saw it. The archbishop took pleasure in explaining the use of it himself, and in making the same experiments which he had seen performed by the inventor at Ratisbon.

The report of these first experiments soon spread through the whole of the learned world of Europe. Father Schott himself gave great publicity to them by publishing, in 1657, his book called "Mechanica Hydraulico-Pneumatica," to which he added, in an appendix, a detailed account of the *Experiments of Madgeburg* (it was thus that they were called). Fresh discoveries, if not more interesting, at least more important, were now daily made by the ingenious burgomaster, who, since his visit to Ratisbon and Wurtzburg, had kept up a scientific connexion with the Archbishop of Mentz, through Father Schott. The latter, who corresponded regularly with a large number of learned men, lost no time in communicating to them the discoveries of the laborious philosopher. Among the new experiments which were made from 1656 to 1664, during which time Father Schott's "Technica Curiosa" appeared, must be mentioned, first of all, that of the *Hemispheres of Madgeburg*. It was performed in the following manner: two hollow copper hemispheres, A and B (fig. 6), were made to fit exactly on one another by means of a disk placed round the circle of each hemisphere. A well greased leathern rundle, D (fig. 7), was interposed between the two disks, so as to join the two hemispheres hermetically, as represented by fig. 8. One of the hemispheres, B, is furnished in its lower part with a cock, through which a vacuum can be produced, and which, when once turned off, did not allow any air to re-enter when the receiver was separated from the air-pump. Both hemispheres were supplied with rings firmly fitted in.

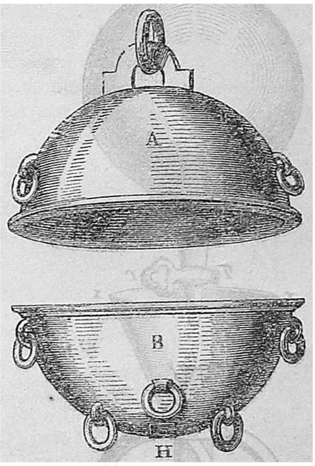

FIG. 6.—Hollow hemispheres separated.

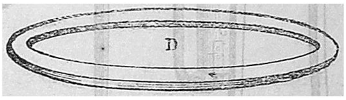

FIG. 7.—Rundle interposed between the two hemispheres.

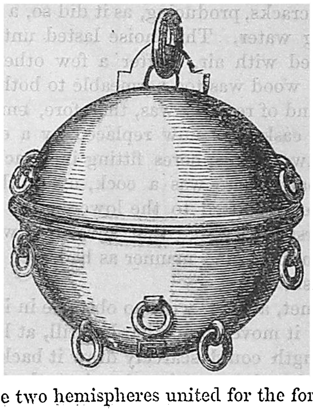

FIG. 8.—The two hemispheres united for the formation of a vacuum.

With the instrument thus arranged, and as the vacuum is being formed in a more perfect manner in the spherical receiver composed of two hemispheres simply placed one on the other, it becomes, every instant, more difficult to separate them; this difficulty augments, also, in proportion as the diameter of the sphere is increased.

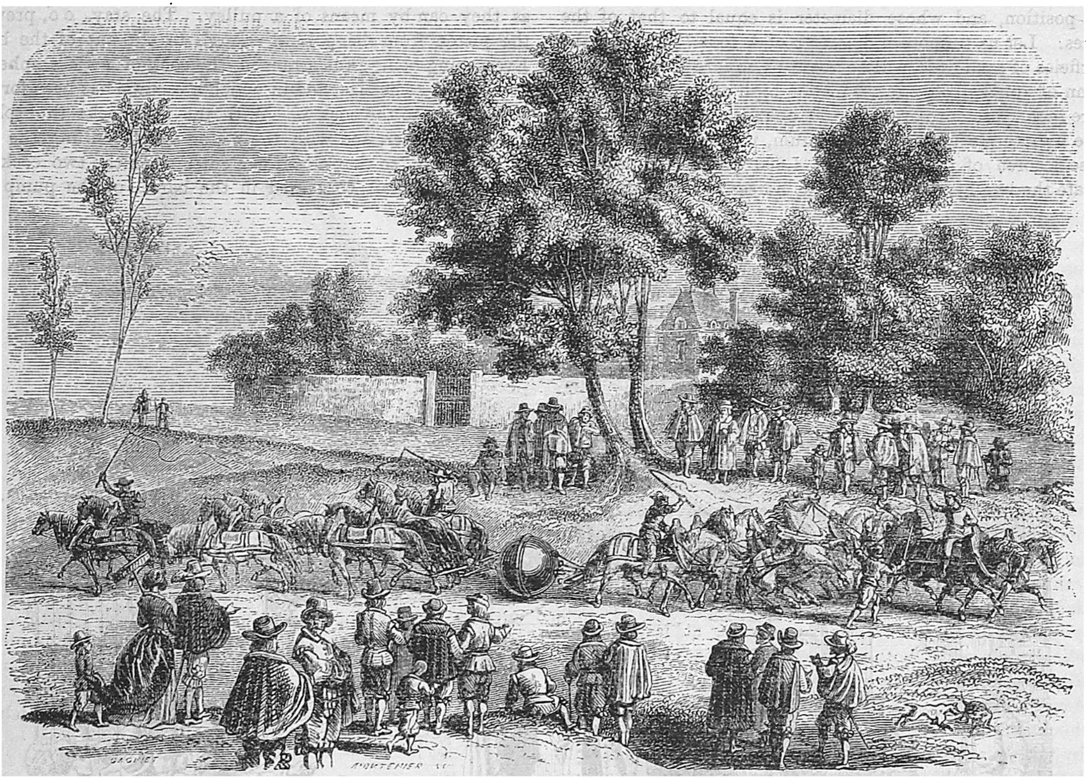

Fig. 9.—Celebrated experiment with the Magdeburg hemispheres.

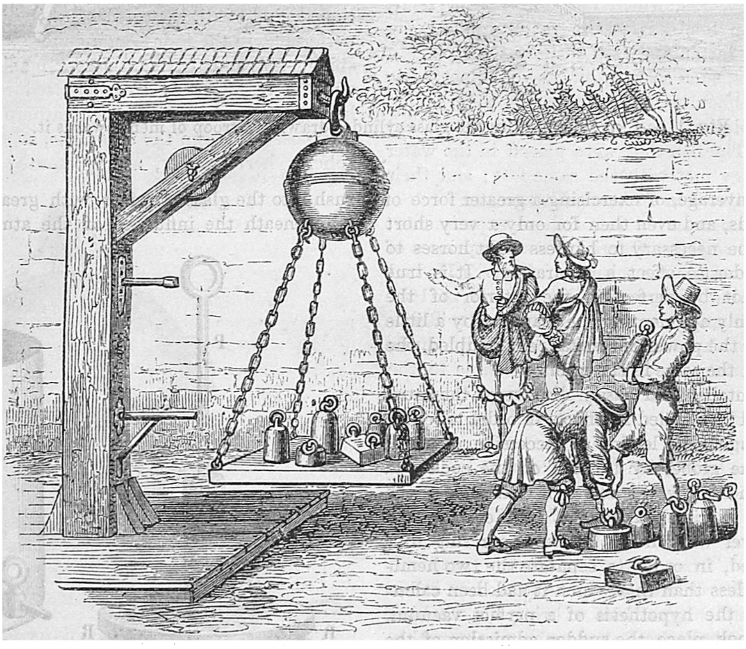

Fig. 10.—Another experiment with the Magdeburg hemispheres.

During his first experiments, in 1656, Otho Guericke asserted that six able-bodied men could not separate the two hemispheres; and, by increasing the diameter and forming a more perfect vacuum, he was able successively to harness to the sphere, twelve, sixteen, twenty, and twenty-four horses, which, though urged on by the whip and by cries, could not, with all their combined force, succeed in effecting a disjunction. Fig. 9 represents this celebrated experiment, after the engraving which Father Schott inserted in his "Technica Curiosa."

It is easy to account for this result, which may at first appear quite impossible. By supposing the existence of a perfect vacuum, the pressure of the atmosphere, which keeps the hemispheres one against the other, acts like two columns of quicksilver about 2 feet 6 inches high, pressing, in opposite directions, against two circular disks placed in juxta-position, and whose diameter is equal to that of the spheres. Let us suppose a diameter of 1 foot 7½ inches; the superficies of each disk will be about 6½ square feet. Now, a column of quicksilver 2 feet 6 inches high exercises on every square inch a pressure of about 56 pounds. Thus, reasoning on the hypothesis of a perfect vacuum, it would be necessary to use a force of traction of full 4,800 pounds in order to separate the two hemispheres. Now, horses, when harnessed, are not capable, on an average, of exercising a greater force of traction than 560 pounds, and even then for only a very short time. It would thus be necessary to harness eight horses to each hemisphere in order to effect a separation. It is true that the vacuum cannot be perfect in the interior of the sphere; but then, by only augmenting the diameter by a little more than half an inch, the power of resistance is doubled, the vacuum being supposed the same in the interior.

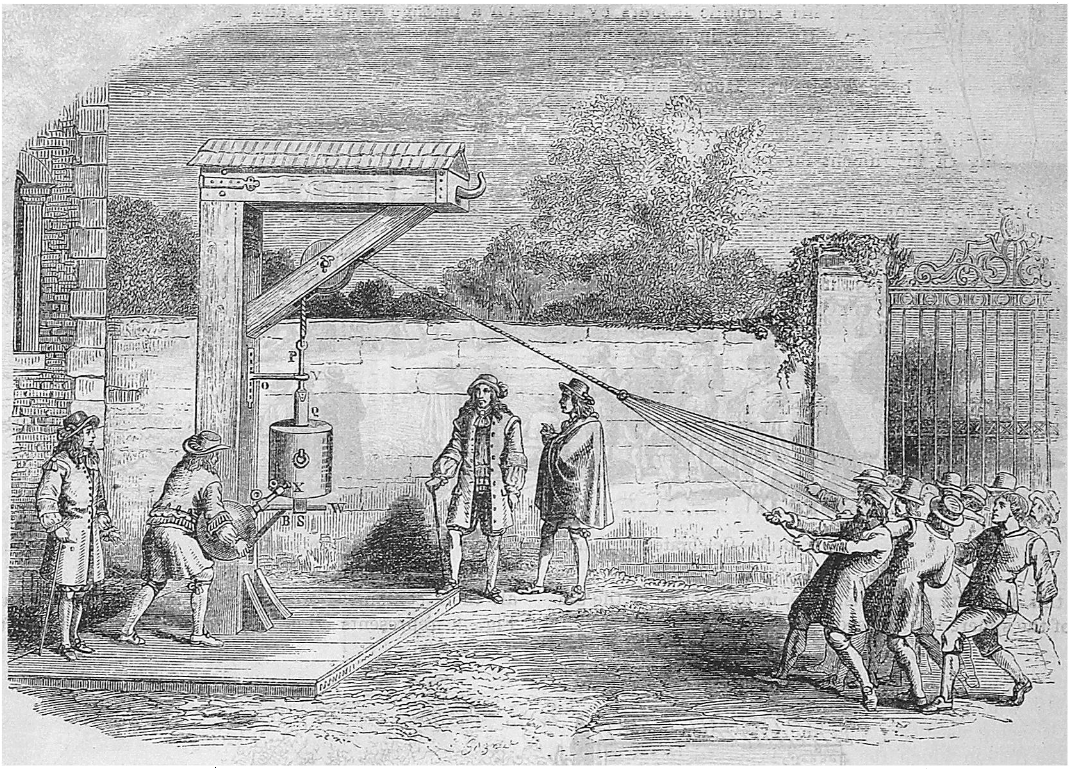

Fig. 11.—Experiments with the glass cylinder drawing a troop of men towards it.

The clever experimentalist had easily discovered the cause of the phenomenon, and had varied its effects in order to render it still more astonishing. By letting a succession of small quantities of air into the globe, by turning on the cock and turning it off again immediately, the power of resistance of the two disks was rapidly diminished, and, at last, entirely destroyed. If the receiver were hung by its upper ring to a strong hook, it required, in order to separate the two hemispheres, a weight little less than that which it had been calculated was necessary in the hypothesis of a perfect vacuum. When the separation took place, the sudden admission of the air produced an explosion similar to that of a piece of artillery. Fig. 10 represents the apparatus employed.

Figs. 11 and 12 clearly explain another experiment, to which the discoverer himself tersely gives the name of "a glass vase, which possesses the force of drawing to it 20, 30, 40, 50, or even a greater number of able-bodied men." The cylindrical barrel of a pump, furnished with a cock, X, rests its lower part on a support, W B. In this barrel works a piston, R R, represented separately in fig. 7, and on the handle of which, Q P, a number of men are exercising as much force of traction as they can by means of a pulley. The stay, O O, prevents the piston from rising high enough to slip out of the band. Everything being thus arranged, the cock of a glass spherical receiver of some size, and in which a vacuum has been formed, is fitted on to the cock X. With the two cocks thus placed one in the other, and with the piston exactly filling the bore of the pump, so that no air can enter when the two cocks are turned on, the air contained in the barrel of the pump will rush into the glass receiver with great force, the piston will fall beneath the influence of the atmospheric pressure, and the men will be dragged towards the pump, in spite of any resistance they may make.

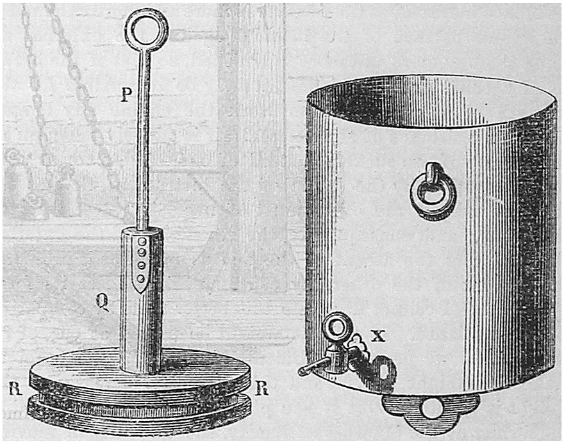

Fig. 12.—Details of the glass cylinder and its piston.

These magnificent experiments have been related by the inventor in a remarkable work, published at Amsterdam, in 1670. An account of them had already appeared, under the title of "Wonders of Madgeburg," in the "Technica Curiosa" of Father Schott, who published as well the "Wonders of England," according to the naïvely enthusiastic style of the epoch. Robert Boyle, a clever English natural philosopher, profiting by the labours of Otho Guericke, had repeated and varied his experiments, had constructed new machines, and had, in a word, gone a step beyond the German philosopher. For a long time the air-pump was designated in England by the name of *Boyle's pump* or *Boyle's vacuum*, but Robert Boyle never claimed priority in this respect. There exists a letter of his written two years after the publication of Father Schott's first work, and in this letter he explicitly states that he was preceded in his scientific labours by the distinguished Otho Guericke. He adds, however, that, in order to remedy certain inconveniences existing in the latter's air-pump, he begged Messrs. Hook and Gratorix to invent some new machines which would be more easy to work, and that, after several useless attempts, Hook succeeded in making an instrument far preferable to the one of Madgeburg.

Robert Boyle soon employed a better engine than the preceding one, but, like that, only furnished with one barrel; and, at last, in order to perform a series of new experiments with a vacuum, he employed a machine different from both of these, and which was the production of the celebrated and unfortunate Frenchman, Denis Papin. In order that no doubt may exist with respect to this subject, we will here give a passage from the celebrated geometrician and philosopher Cotes, of whom Newton himself said, that, "if Mr. Cotes had lived, we should know something." The following is the passage, extracted from the lectures given at Cambridge by Cotes on experimental physics.

This machine "was the contrivance of Mr. Papin, whose assistance Mr. Boyle did also make use of in the trials themselves. This third air-pump was much more convenient than the former, and the advantage lay chiefly in these two particulars. First, whereas the former engines had only one single barrel and one sucker or embolus, this was furnished with two barrels and two suckers, and these two suckers being alternately raised and depressed, caused the evacuation to be continual; which effect could not be obtained by a single sucker, it being necessary that the evacuation should cease during the time in which the sucker is forced in towards the bottom of the barrel. But, besides this advantage of performing the operation in half the time it could be done with a single sucker, the labour also in doing it was greatly lessened. The chief difficulty complained of in single-barrelled pumps is the very great resistance which the external air makes against the sucker as it is drawn outwards; and this resistance increases as the receiver is more and more exhausted, the counterbalance of the internal against the external air being thereby more and more diminished, so that if the barrel be of a considerable wideness, it may be impossible for the strength of any one man to work the engine any longer. Now this resistance of the external air is entirely taken off by making use of two suckers instead of one. They are so connected together by the fabric of the instrument, that as the one descends, so the other must of necessity ascend at the same time; and, consequently, the resistance of the external air, hindering the ascent of the one as much as it promotes the descent of the other, by contrary effects loses its force upon both. I cannot illustrate this better than by comparing it with a balance. If a single weight be placed at one of its extremities, we perceive a difficulty in moving the beam to make the weight ascend, and this difficulty increases as the weight is greater. But if you place another weight equal to the former at the opposite extremity, the difficulty in moving the beam will entirely cease, how great soever the two equal weights may be supposed to be.

"The other particular in which this air-pump excelled the former, was the advantage of its valves. In the two first engines, whilst the sucker was drawn outwards, you was obliged at the same time to turn a stop-cock, to make way for the air in the receiver to pass from thence into the barrel; and when this air was to be excluded from the barrel, as the sucker was moved inwards, you was obliged again to turn the stop-cock, to prevent the air from reverting into the receiver; and at the same time to give it a passage outwards, a stopple or plug was to be removed, which closed the hole through which it was to pass, and then again this hole was to be stopped up and the cock to be turned again as more air was drawn from the receiver, and this labour to be repeated perpetually, so long as you continued to work the pump. Now the valves which, in the third air-pump, supplied the place of the plug and stop-cock, were undoubtedly much more convenient, in that of themselves they opened to give the air a passage forwards, and shut to prevent its return back again."

Fig. 13 represents an apparatus arranged according to this system, of which the following is a summary description:—

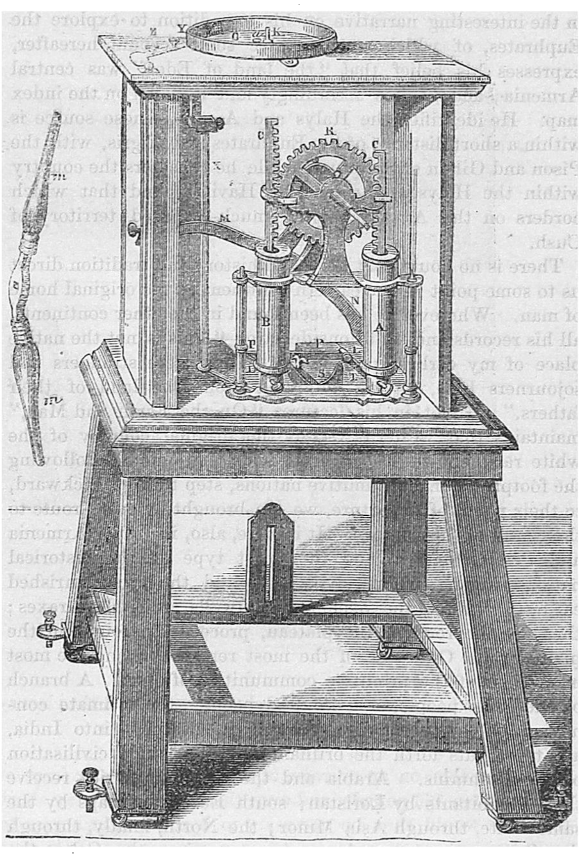

FIG. 13.—Double-acting pneumatic machine, according to the system of Papin.

A and B are two cylinders, in each of which is a piston. The rods, C, of the pistons are furnished with teeth, and they are worked by means of a wheel, R, which in its alternate movement describes about the third of a circle. On the plate, G, are placed the vessels from which it is required to expel the air, and which communicate by pipes, X X X, with the cylinders. Each of these pumps is furnished with a cock placed a little below their ends. The handles of these cocks are indicated by L L, and they are connected one with the other by the brass rod P P, so that both cocks are always moved together. To the axle-tree of the wheel, R, is joined, from behind, a sort of iron cross, N M, which turns the cocks. This ingenious piece of mechanism is rather more complicated than that of the simple valves; but its principle is the same, while it is, perhaps, the means of closing any vessel in a more hermetical manner.